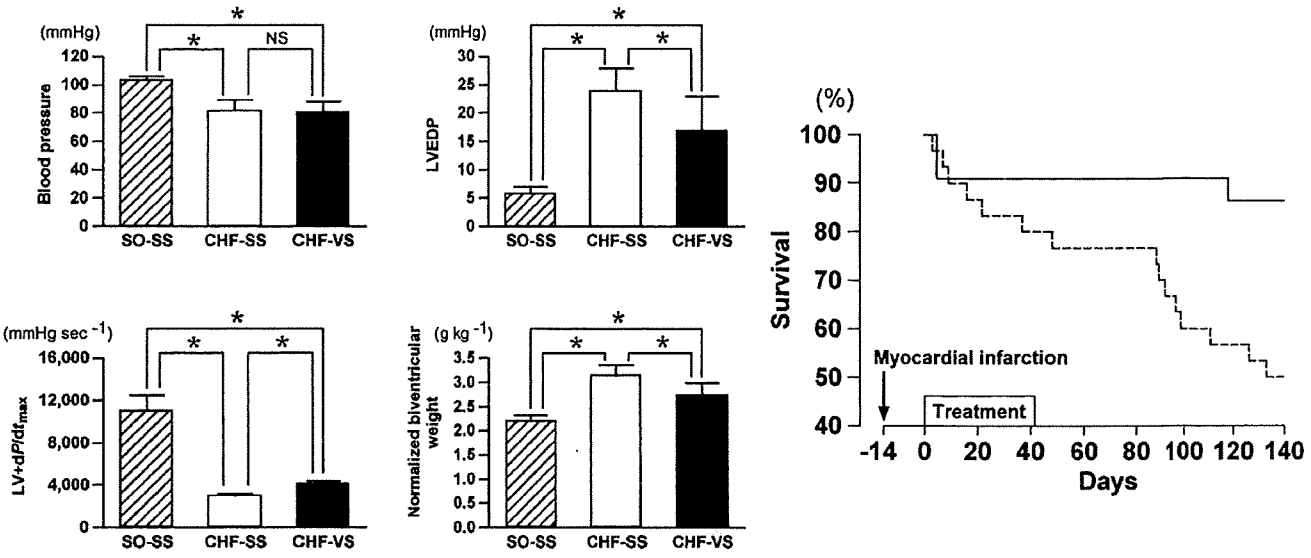

Fig. 7. Forty-two-day right vagal stimulation attenuated increased LVEDP, decreased maximal rate of left ventricular pressure rise (LV $+dP/dt_{max}$), increased normalized biventricular weight (left). SO-SS: sham-stimulated rats without failure (n = 9); CHF-SS: sham-stimulated rats with heart failure (n = 13); CHF-VS: vagal-stimulated rats with heart failure (n = 11); (*) $p < 0.05$. Survival for 140 days of rats with (solid line, n = 22) or without (dashed line, n = 30) 42-day vagal stimulation (right). (Reproduced from [78] with permission.)

Although the primary cause of heart failure is decreased pump function, the adjunct neurohumoral activation is certainly a major aggravating factor for disease progression and risk of death. Clinical trials on drugs for heart failure have revealed repeatedly that suppression of neurohumoral factors rather than increasing cardiac contractility improves survival. Pharmacological activation of vagal tone (such as low-dose scopolamine) [77] has been evaluated, but the effects on long-term survival have not been shown. With this background, bionic device therapy counteracting activated neurohumoral factors has been developed.

B. *Vagal Nerve Stimulation in Animal Studies*

Li *et al.* [78] first demonstrated that direct electrical stimulation of right vagal nerve (started after healing of extensive myocardial infarction) was effective in delaying the progression of heart failure and drastically improving survival in rats with heart failure. The intensity of vagal stimulation was low (decreasing heart rate by approximately 10%) enough to avoid adverse effects. They showed that vagal stimulation (control, n = 13; vagal stimulation, n = 11) significantly decreased left ventricular filling pressure from 24 ± 4 to 17 ± 6 mmHg, increased left ventricular $+dp/dt_{max}$ from 2987 ± 192 to 4152 ± 37 mmHg/s and decreased biventricular weight from 3.1 ± 0.2 to 2.8 ± 0.3 g/kg body weight, although the size of infarction was unchanged. Vagal nerve stimulation markedly improved survival from 50% to 82% ($p < 0.01$) at 140 days (Fig. 7). The same group also showed that vagal stimulation suppressed arrhythmias [79] and decreased both vasopressin secretion and salt ingestion [80]. The latter indicates the possible contribution of central modification induced by afferent nerve stimulation. Heart rate decreased progressively in six weeks. Vagal nerve stimulation protected the heart against acute ischemia, as well as reduced norepinephrine [81] and myoglobin [82] (an index of myocardial injury) release. These effects were attributed to its bradycardiac effect. Uemura *et al.* [83] investigated the effect of vagal nerve stimulation (−15 to 240 min) on matrix metalloproteinase (MMP) activity in a rabbit model of ischemia (60 min)-reperfusion (180 min) injury. Vagal stimulation increased the expression of tissue inhibitor of MMP-1 (TIMP-1) in cardiomyocytes and reduced active MMP-9. These molecular mechanisms of vagal stimulation might help prevent cardiac remodeling.

Some of the beneficial effects of vagal stimulation in heart failure may involve anti-inflammatory pathways. A large body of evidence [84]–[89] indicates that both afferent and efferent vagal nerves form anti-inflammatory pathways. The afferent vagal nerve senses local inflammation and transmits the information to the brain to suppress excessive inflammatory response in other areas in which inflammation may be elicited by the diffusion of various cytokines. In addition to recruiting the hypothalamic-pituitary-adrenal axis to release corticoids, the efferent vagal nerve is activated for faster anti-inflammatory response. The efferent activity stimulates nicotinic receptors on macrophages [84], and nicotinic alpha7 unit is essential for this regulation [86]. Activation of nicotinic receptors inhibits the release of pro-inflammatory cytokines such as TNF-alpha, IL-5, and IL-18 but does not inhibit the anti-inflammatory cytokine IL-10 [84]. Efferent vagal nerve stimulation is shown to decrease liver NF-kappa B, reduce plasma TNF-alpha, and revert hypotension in hemorrhagic shock (besides septic shock) through nicotinic receptors [89]. These findings indicate the involvement of inflammatory response in life-threatening cardiovascular disease such as hemorrhagic shock and heart failure.

C. *Vagal Nerve Stimulation in Patients With Heart Failure*

Recently, an implantable chronic vagal neurostimulator has entered clinical trial [90]. In this small-sized trial, the stimu-

lator (Cardiofit, BioControl) was implanted in 32 patients with heart failure (NYHA II to III, ejection fraction $\leq$ 35%). The right vagal nerve was stimulated intermittently (4 mA, 21% on). Heart rate decreased from 82 to 76 bpm; quality-of-life score (Minnesota Living with Heart Failure Questionnaire) improved from 48 to 32; 6-min walk increased from 410 to 471 m; and left ventricular ejection fraction increased from 23% to 27% in six months. The impact of vagal stimulation on the hard endpoint in these patients remains to be seen.

D. Carotid Sinus Nerve Stimulation in Heart Failure

Zucker *et al.* [91] examined if carotid sinus nerve stimulation (CVRx) improves the survival of dogs with pacing-induced (250 bpm) heart failure. They continued tachypacing until the endpoint (death or moribund state) was reached. Although the progression of heart failure (indicated by left ventricular end-diastolic pressure, left ventricular $+dp/dt_{max}$, mean arterial pressure, heart rate, ejection fraction) was similar between dogs with and without carotid sinus nerve stimulation, increases in norepinephrine and angiotensin II were delayed in dogs with carotid sinus nerve stimulation. Dogs with carotid sinus nerve stimulation survived longer. How this observation translates to the clinical impact of carotid sinus nerve stimulation in patients with heart failure remains to be investigated.

VII. Autopilot Treatment of Acute Decompensated Heart Failure

Although neurohumoral suppression is the mainstay of long-term treatment for heart failure, a different strategy is required when the hemodynamics are acutely exacerbated. In order to save the lives of such patients, vital hemodynamic variables including blood pressure, cardiac output, and left atrial pressure have to be maintained within physiological ranges. Abnormality in each of these variables should be corrected promptly. The management of hemodynamic decompensation requires complex control of infusions of multiple potent drugs. The advent of automated feedback control of multiple drug infusions would have a major impact on clinical medicine. Such closed-loop feedback treatment involves control engineering and electronic controllers. This is also an important area of bionic cardiology.

A. Development of Integrative Cardiovascular Model

Various modalities of feedback control of hemodynamic variables using drug infusion have been attempted [92], [93], including those that control two variables. These attempts were only partially successful due to the complex interaction between variables. Results of these investigations prompted Uemura *et al.* [94], [97], [98] to take a different approach for hemodynamic control. They first established methods to break down each hemodynamic variable into fundamental physiological properties of the cardiovascular system. This was achieved by modeling the total cardiovascular system as the interaction of three different components: left heart pump, right heart pump, and total (systemic and pulmonary) vasculature [94], [96]. The model is an extension of Guyton's cardiovascular model [95] but differs from Guyton's model in several aspects: a third axis is incorporated to explicitly express left atrial pressure; the left and right heart pump functions are defined independently; and blood redistribution between systemic and pulmonary vasculature is expressed on the same venous return surface [Fig. 8(A)]. Using this model, Uemura *et al.* [94], [97] succeeded in delineating fundamental determinants of hemodynamics (left heart pump function, right heart pump function, systemic vascular resistance, and total stressed blood volume) from clinically measurable variables (blood pressure, cardiac output, left atrial pressure, and right atrial pressure).

B. Bionic Treatment of Decompensated Heart Failure

Based on their new model, Uemura *et al.* [98] designed a bionic controller that can simultaneously normalize blood pressure, cardiac output, and left atrial pressure accurately, quickly, and stably [Fig. 8(B)]. Their success is based on the effective decoupling of the complex interaction between variables, thereby allowing them to design three independent feedback control loops: left heart pump function controlled by an inotropic agent (dobutamine), systemic vascular resistance controlled by a vasodilator (sodium nitroprusside), and total stressed blood volume controlled by a volume expander and/or a diuretic (dextran solution, furosemide). Using the controller in 12 anesthetized dogs with severely decompensated heart failure restored the pump function, vascular resistance, and blood volume to normal levels in 30 min. As a result, blood pressure was controlled within 4.4 ± 2.6 mmHg, cardiac output within 5.4 ± 2.4 ml/min/Kg, and left atrial pressure within 0.8 ± 0.6 mmHg for another 30 min. The average amounts of drug use was dobutamine 4.7 ± 2.6 μg/min/kg, nitroprusside 4.2 ± 1.8 μg/min/kg, dextran infusion 2.4 ± 1.9 mL/kg, and furosemide 10 mg in one dog and 20 mg in another dog [Fig. 8(C)]. Even using the classical proportional-integral control for dobutamine and nitroprusside infusions and the "if-then" rule control for dextran/furosemide, control of multiple hemodynamic variables was possible and of good quality.

C. Beyond Hemodynamic Stabilization

Uemura *et al.* [99] attempted to further elaborate the treatment of decompensated heart failure beyond hemodynamic stabilization. They added myocardial oxygen consumption as an additional target for electronic control. The heart is an organ that consumes a large amount of oxygen and is highly vulnerable to oxygen shortage. Hayashida *et al.* [100] have shown in conscious dogs that the heart optimizes its metabolic efficiency during exercise as well as at rest. Theoretically, the optimal heart rate minimizes oxygen consumption for a given blood pressure, cardiac output, and left atrial pressure [101]. Uemura *et al.* [99] demonstrated in conscious dogs with acute decompensated heart failure that the automated electronic system of hemodynamic management allowed them to pharmacologically lower heart rate and myocardial oxygen consumption without compromising hemodynamics. The model-based approach to simultaneous optimization of multiple variables would help improve the outcome of patients with hemodynamic decompensation.

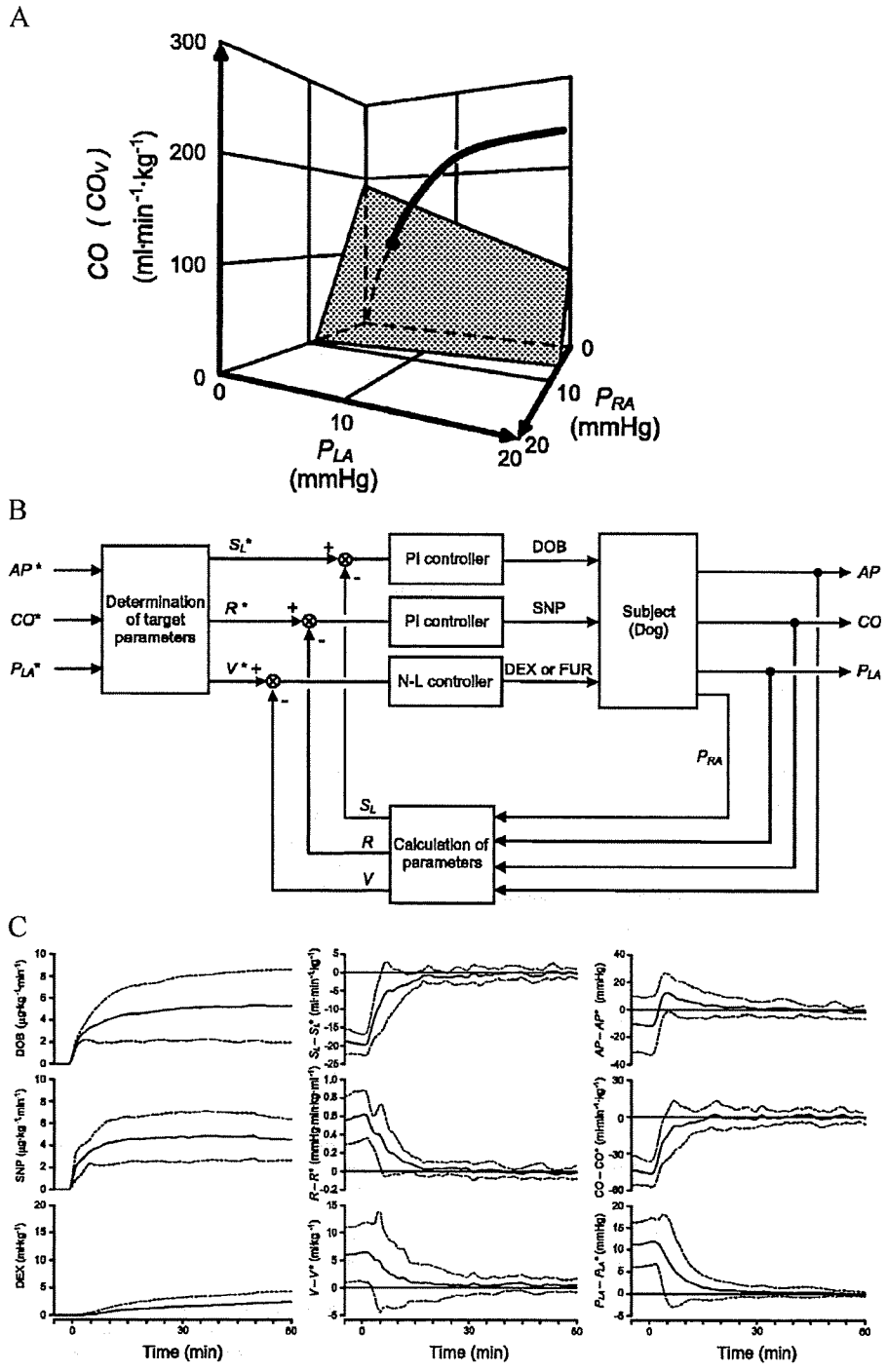

Fig. 8. (A) Extended Guyton's model of the total cardiovascular system. A third axis explicitly expresses left atrial pressure (P_{LA}), a cardiac output curve expresses left and right heart pump function independently, and a venous return surface expresses blood distribution in vasculatures. P_{RA}: right atrial pressure; CO: cardiac output; CO_V: venous return (= cardiac output). (B) Block diagram of an autopilot system for simultaneous control of systemic arterial pressure (AP), CO, and P_{LA}. Parameters with (*) indicate target values. From target variables, target values of left heart pump function (S_L), stressed blood volume (V), and systemic vascular resistance (R) are determined. S_L, V, and R of subjects are calculated from measured AP, CO, P_{LA}, and P_{RA}. Proportional-integral (PI) controllers adjust infusion rate of dobutamine (DOB) and sodium nitroprusside (SNP) to minimize the error in S_L and R, respectively. If-then rules adjust infusion of 10% dextran 40 (DEX) or injection of furosemide (FUR) to minimize the error in V. (C) Automatic correction of acute decompensated heart failure. Errors in cardiovascular properties (middle panels) (S_L, R, V) rapidly approached to zero, resulting in cardiovascular variables (right panels) (AP, CO, P_{LA}) approaching respective target. Left panels indicate infusion rate of DOB, SNP, and infused volume of DEX. (Reproduced from [98] with permission.)

VIII. Future of Bionic Medicine

We foresee a promising future for bionic medicine. It appears, however, that various factors may significantly influence the development and promotion of bionic cardiology. The first is the technology to interface native regulatory systems with bionic systems. The latest technology has made it possible to physically interface electronic devices with cardiac tissues (pacemaker, ICD). Neural interface, however, leaves much room for

improvement in terms of selectivity, stability, and durability. Sophistication of physical as well as logical neural interface will no doubt facilitate intricate body control. An advanced interface that allows stimulation at lower electrical power by minimizing current leakage and fully utilizing native excitation function will reduce adverse effects. Appropriate methods for the selective measurement and/or stimulation of subgroup of nerve fibers are necessary to match the spatial resolution indicated by the physiological/medical requirements. Autonomic function may be the first controllable function in the clinical setting compared to sensory or motor functions where intricate neural interface for higher spatial and temporal resolution is mandatory.

The second is the development of implantable long-term sensors. This factor would appear to be one of the basic needs, but has been relatively ignored until recently. For years, measurements have been limited to electrical signals. No durable sensors for mechanical or chemical variables are available. Once implanted, it is necessary to keep its accuracy even in blood for a considerably long term without repeated recalibrations. Therefore, the requirements of such sensors include long-term durability, stability, anticoagulation nature, and no need for recalibration.

The third is technology to support communication mechanisms in the body. Since the operation of bionic system is based on a closed feedback mechanism, various feedback loop components including sensors, controllers, actuators and plant have to communicate mutually. In the body, the neurohormonal mechanisms support this communication. In the bionic system, however, if some of these components are physically distant from each other, artificial communication mechanisms are needed for closed loop operation. We await the development of such an artificial communication mechanism in the body. The communication should simultaneous satisfy the short delay time (for real-time operation and closed-loop feedback), the sufficient bandwidth (depending on the application), the avoidance from interference from other communications and noises (guaranteeing secure feedback operation), and the mission-critical security (for medical need).

The fourth is the mechanism to support the power of bionic devices. This has been a significant problem, and will remain a target for research. The battery life should be long enough to be clinically meaningful. The size is preferable as small as possible. This is because the size of power supplies often determines that of the implantable devices. The third and fourth technology, if realized and combined, may obviate the use of leads, the most fragile part of implantable devices.

The fifth is the development of integrative science for biological system. To design elaborate feedback regulation of the cardiovascular system, in-depth knowledge of biological regulation is essential. Moreover, as already discussed in the Introduction, we have to go beyond the restoration of biological regulation to combat common diseases. Biological regulation has to be translated into and expressed in the "language" of control engineering. The expression should include dynamic, multiple-input, interactive, nonlinear, and feedback natures of the total system concerned. Besides these, we have to develop a model incorporating the effect of modifying biological regulation on the progression of common diseases. The development of such a model definitely requires biological research. Investigations of integrative biological regulation mandate the knowledge of both biology and engineering. It is our hope that many biomedical engineers will participate in the exploration into the development of bionic medicine.

The last factor is medical needs. Recent interest in device-based therapy will uncover the potential of bionic medicine in meeting the unmet needs. Of various cardiovascular diseases presented in this paper, the need for the appropriate treatment of chronic heart failure is most seriously unmet. Device-based therapy including bionic medicine is expected to complement existing treatment modalities to provide therapeutic benefits that cannot be achieved by drugs alone, especially for the increasing patients of chronic heart failure.

In conclusion, bionic medicine is the science to explore the wealth of controllable body parts. Bionic cardiology has a long history, through which we have accumulated much experience, generated knowledge on biological regulation, and identified unmet needs. These unique features together put us in a strong position to promote the development of more sophisticated device-based therapy for otherwise untreatable diseases. Bionic medicine will inspire more intricate applications in the twenty-first century.

REFERENCES

[1] T. Kawada and M. Sugimachi, "Artificial neural interfaces for bionic cardiovascular treatments," *J. Artif. Organs*, vol. 12, no. 1, pp. 17–22, Mar. 2009.

[2] M. Sugimachi and K. Sunagawa, "Bionic cardiovascular medicine. Functional replacement of native cardiovascular regulation and the correction of its abnormality," *IEEE Eng. Med. Biol. Mag.*, vol. 24, pp. 24–31, Jul.-Aug. 2005.

[3] T. Kubota, H. Chishaki, T. Yoshida, K. Sunagawa, A. Takeshita, and Y. Nose, "How to encode arterial pressure into carotid sinus nerve to invoke natural baroreflex," *Amer. J. Physiol.*, vol. 263, no. 1, pp. H307–H313, Jul. 1992.

[4] Y. Ikeda, M. Sugimachi, T. Yamasaki, O. Kawaguchi, T. Shishido, T. Kawada, J. Alexander Jr., and K. Sunagawa, "Explorations into development of a neurally regulated cardiac pacemaker," *Amer. J. Physiol.*, vol. 269, no. 6, pp. H2141–H2146, Dec. 1995.

[5] T. Sato, T. Kawada, T. Shishido, M. Sugimachi, J. Alexander Jr., and K. Sunagawa, "Novel therapeutic strategy against central baroreflex failure: A bionic baroreflex system," *Circulation*, vol. 100, no. 3, pp. 299–304, Jul. 1999.

[6] T. Sato, T. Kawada, M. Sugimachi, and K. Sunagawa, "Bionic technology revitalizes native baroreflex function in rats with baroreflex failure," *Circulation*, vol. 106, no. 6, pp. 730–734, Aug. 2002.

[7] M. Sugimachi, T. Imaizumi, K. Sunagawa, Y. Hirooka, K. Todaka, A. Takeshita, and M. Nakamura, "A new method to identify dynamic transduction properties of aortic baroreceptors," *Amer. J. Physiol.*, vol. 258, no. 3, pp. H887–H895, Mar. 1990.

[8] T. Kawada, Y. Ikeda, M. Sugimachi, T. Shishido, O. Kawaguchi, T. Yamazaki, J. Alexander Jr., and K. Sunagawa, "Bidirectional augmentation of heart rate regulation by autonomic nervous system in rabbits," *Amer. J. Physiol.*, vol. 271, no. 1, pp. H288–H295, Jul. 1996.

[9] T. Kawada, M. Sugimachi, T. Shishido, H. Miyano, Y. Ikeda, R. Yoshimura, T. Sato, H. Takaki, J. Alexander Jr., and K. Sunagawa, "Dynamic vagosympathetic interaction augments heart rate response irrespective of stimulation patterns," *Amer. J. Physiol.*, vol. 272, no. 5, pp. H2180–H2187, May 1997.

[10] T. Sato, T. Kawada, M. Inagaki, T. Shishido, H. Takaki, M. Sugimachi, and K. Sunagawa, "New analytic framework for understanding sympathetic baroreflex control of arterial pressure," *Amer. J. Physiol.*, vol. 276, no. 6, pp. H2251–H2261, Jun. 1999.

[11] T. Kawada, T. Shishido, M. Inagaki, C. Zheng, Y. Yanagiya, K. Uemura, M. Sugimachi, and K. Sunagawa, "Estimation of baroreflex gain using a baroreflex equilibrium diagram," *Jpn. J. Physiol.*, vol. 52, no. 1, pp. 21–29, Feb. 2002.

[12] T. Sato, T. Kawada, M. Inagaki, T. Shishido, M. Sugimachi, and K. Sunagawa, "Dynamics of sympathetic baroreflex control of arterial pressure in rats," *Amer. J. Physiol.*, vol. 285, no. 1, pp. R262–R270, Jul. 2003.

[13] Y. Ikeda, T. Kawada, M. Sugimachi, O. Kawaguchi, T. Shishido, T. Sato, H. Miyano, W. Matsuura, J. Alexander Jr., and K. Sunagawa, "Neural arc of baroreflex optimizes dynamic pressure regulation in achieving both stability and quickness," *Amer. J. Physiol.*, vol. 271, no. 3, pp. H882–H890, Sep. 1996.

[14] K. Sunagawa, T. Sato, and T. Kawada, "Integrative sympathetic baroreflex regulation of arterial pressure," *Ann. NY Acad. Sci.*, vol. 940, pp. 314–323, Jun. 2001.

[15] A. J. Linenthal, "Quantitative studies in man of the cardiovascular effects of reflex vagal stimulation produced by carotid sinus pressure. I. Localization of an increased effect in a patient with angina pectoris," *Circulation*, vol. 5, no. 1, pp. 81–84, Jan. 1952.

[16] E. Braunwald, S. E. Epstein, G. Glick, A. S. Wechsler, and N. S. Braunwald, "Relief of angina pectoris by electrical stimulation of the carotid-sinus nerves," *New Eng. J. Med.*, vol. 277, no. 24, pp. 1278–1283, Dec. 1967.

[17] S. I. Schwartz, L. S. Griffith, A. Neistadt, and N. Hagfors, "Chronic carotid sinus nerve stimulation in the treatment of essential hypertension," *Amer. J. Surg.*, vol. 114, no. 1, pp. 5–15, Jul. 1967.

[18] Y. Nakayama, H. Miyano, T. Shishido, M. Inagaki, T. Kawada, M. Sugimachi, and K. Sunagawa, "Heart rate-independent vagal effect on end-systolic elastance of the canine left ventricle under various levels of sympathetic tone," *Circulation*, vol. 104, no. 19, pp. 2277–2279, Nov. 2001.

[19] E. Braunwald, S. F. Vatner, N. S. Braunwald, and B. E. Sobel, "Carotid sinus nerve stimulation in the treatment of angina pectoris and supraventricular tachycardia," *Calif. Med.*, vol. 112, no. 3, pp. 41–50, Mar. 1970.

[20] D. T. Mason, J. F. Spann, Jr, R. Zelis, and E. A. Amsterdam, "Physiologic approach to the treatment of angina pectoris," *New Eng. J. Med.*, vol. 281, no. 22, pp. 1225–1228, Nov. 1969.

[21] S. F. Vatner, D. Franklin, R. L. Van Citters, and E. Braunwald, "Effects of carotid sinus nerve stimulation on blood-flow distribution in conscious dogs at rest and during exercise," *Circ. Res.*, vol. 27, no. 4, pp. 495–503, Oct. 1970.

[22] F. Solti, S. Juhász-Nagy, Z. Szabó, M. Iskum, and I. Krasznai, "Effect of the carotid sinus nerve stimulation on nutritive myocardial blood flow in regional cardiac ischaemia," *Basic Res. Cardiol.*, vol. 70, no. 5, pp. 531–536, Sep.-Oct. 1975.

[23] F. Solti and A. Jahász-Nagy, "Effect of carotid sinus nerve stimulation on coronary blood flow in myocardial ischaemia: Role of the collateral vessels," *Basic Res. Cardiol.*, vol. 70, no. 6, pp. 639–646, Nov.-Dec. 1975.

[24] S. E. Epstein, G. D. Beiser, R. E. Goldstein, D. Redwood, D. R. Rosing, G. Glick, A. S. Wechsler, M. Stampfer, L. S. Cohen, R. L. Reis, N. S. Braunwald, and E. Braunwald, "Treatment of angina pectoris by electrical stimulation of the carotid-sinus nerves," *New Eng. J. Med.*, vol. 280, no. 18, pp. 971–978, May 1969.

[25] "Electrical stimulation of the carotid-sinus nerves for angina pectoris," *Lancet*, vol. 294, no. 7616, pp. 362–364, Aug. 1969.

[26] N. S. Braunwald, S. E. Epstein, and E. Braunwald, "Carotid sinus nerve stimulation for the treatment of intractable angina pectoris: Surgical technic," *Ann. Surg.*, vol. 172, no. 5, pp. 870–876, Nov. 1970.

[27] R. Courbier, J. Torresani, J. Houzé, A. Jouve, and E. Henry, "Carotid sinus nerve stimulation in angina pectoris," *J. Cardiovasc. Surg. (Torino)*, vol. 12, no. 3, pp. 231–234, May-Jun. 1971.

[28] H. P. Krayenbühl, W. Meier, and W. Burian, "Die Behandlung der Angina Pectoris Durch elektrische Stimulation der Karotissinusnerven (Treatment of angina pectoris by electric stimulation of the carotid sinus nerves)," (in German) *Schweiz. Med. Wochenschr.*, vol. 102, no. 47, pp. 1739–1741, Nov. 1972.

[29] "Carotid-sinus-nerve electro-stimulation in angina pectoris," *Lancet*, vol. 301, no. 7798, p. 304, Feb. 1973.

[30] J. C. Lopshire, X. Zhou, C. Dusa, T. Ueyama, J. Rosenberger, N. Courtney, M. Ujhelyi, T. Mullen, M. Das, and D. P. Zipes, "Spinal cord stimulation improves ventricular function and reduces ventricular arrhythmias in a canine postinfarction heart failure model," *Circulation*, vol. 120, no. 4, pp. 286–294, Jul. 2009.

[31] G. H. Heidorn and A. P. McNamara, "Effect of carotid sinus stimulation on the electrocardiograms of clinically normal individuals," *Circulation*, vol. 14, no. 6, pp. 1104–1113, Dec. 1956.

[32] B. Lown and S. A. Levine, "The carotid sinus. Clinical value of its stimulation," *Circulation*, vol. 23, pp. 766–789, May 1961.

[33] Y. Zhang, K. A. Mowrey, S. Zhuang, D. W. Wallick, Z. B. Popović, and T. N. Mazgalev, "Optimal ventricular rate slowing during atrial fibrillation by feedback AV nodal-selective vagal stimulation," *Amer. J. Physiol.*, vol. 282, no. 3, pp. H1102–H1110, Mar. 2002.

[34] Y. Zhang, H. Yamada, S. Bibevski, S. Zhuang, K. A. Mowrey, D. W. Wallick, S. Oh, and T. N. Mazgalev, "Chronic atrioventricular nodal vagal stimulation: First evidence for long-term ventricular rate control in canine atrial fibrillation model," *Circulation*, vol. 112, no. 19, pp. 2904–2911, Nov. 2005.

[35] S. Zhuang, Y. Zhang, K. A. Mowrey, J. Li, T. Tabata, D. W. Wallick, Z. B. Popović, R. A. Grimm, A. Natale, and T. N. Mazgalev, "Ventricular rate control by selective vagal stimulation is superior to rhythm regularization by atrioventricular nodal ablation and pacing during atrial fibrillation," *Circulation*, vol. 106, no. 14, pp. 1853–1858, Oct. 2002.

[36] J. P. DiMarco, "Selective vagal stimulation for rate control in atrial fibrillation," *Circulation*, vol. 106, no. 14, pp. 1746–1747, Oct. 2002.

[37] S. H. Hohnloser, K. H. Kuck, and J. Lilienthal, "Rhythm or rate control in atrial fibrillation—Pharmacological intervention in atrial fibrillation (PIAF): A randomised trial," *Lancet*, vol. 356, no. 9244, pp. 1789–1794, Nov. 2000.

[38] S. Bianchi, P. Rossi, A. D. Scala, and L. Kornet, "Endocardial transcatheter stimulation of the AV nodal fat pad: Stabilization of rapid ventricular rate response during atrial fibrillation in left ventricular failure," *J. Cardiovasc. Electrophysiol.*, vol. 20, no. 1, pp. 103–105, Jan. 2009.

[39] B. L. Bufkin, J. D. Puskas, J. Vinten-Johansen, S. T. Shearer, and R. A. Guyton, "Controlled intermittent asystole: Pharmacologic potentiation of vagal-induced asystole," *Ann. Thorac. Surg.*, vol. 66, no. 4, pp. 1185–1190, Oct. 1998.

[40] M. Scanavacca, C. F. Pisani, D. Hachul, S. Lara, C. Hardy, F. Darrieux, I. Trombetta, C. E. Negrão, and E. Sosa, "Selective atrial vagal denervation guided by evoked vagal reflex to treat patients with paroxysmal atrial fibrillation," *Circulation*, vol. 114, no. 9, pp. 876–885, Aug. 2006.

[41] D. Cerati and P. J. Schwartz, "Single cardiac vagal fiber activity, acute myocardial ischemia, and risk for sudden death," *Circ. Res.*, vol. 69, no. 5, pp. 1389–1401, Nov. 1991.

[42] P. J. Schwartz, E. Vanoli, M. Stramba-Badiale, G. M. De Ferrari, G. E. Billman, and R. D. Foreman, "Autonomic mechanisms and sudden death. New insights from analysis of baroreceptor reflexes in conscious dogs with and without a myocardial infarction," *Circulation*, vol. 78, no. 4, pp. 969–979, Oct. 1988.

[43] M. T. La Rovere, J. T. Bigger, Jr, F. I. Marcus, A. Mortara, and P. J. Schwartz, "Baroreflex sensitivity and heart-rate variability in prediction of total cardiac mortality after myocardial infarction," *Lancet*, vol. 351, no. 9101, pp. 478–484, Feb. 1998.

[44] G. Zuanetti, G. M. De Ferrari, S. G. Priori, and P. J. Schwartz, "Protective effect of vagal stimulation on reperfusion arrhythmias in cats," *Circ. Res.*, vol. 61, no. 3, pp. 429–435, Sep. 1987.

[45] M. Ando, R. G. Katare, Y. Kakinuma, D. Zhang, F. Yamasaki, K. Muramoto, and T. Sato, "Efferent vagal nerve stimulation protects heart against ischemia-induced arrhythmias by preserving connexin43 protein," *Circulation*, vol. 112, no. 2, pp. 164–170, Jul. 2005.

[46] L. S. Griffith and S. I. Schwartz, "Reversal of renal hypertension by electrical stimulation of the carotid sinus nerve," *Surgery*, vol. 56, pp. 232–239, Jul. 1964.

[47] A. M. Bilgutay and C. W. Lillehei, "Treatment of hypertension with an implantable electronic device," *J. Amer. Med. Assoc.*, vol. 191, pp. 649–653, Feb. 1965.

[48] A. Carlsten, B. Folkow, G. Grimby, C. A. Hamberger, and O. Thulesius, "Cardiovascular effects of direct stimulation of the carotid sinus nerve in man," *Acta. Physiol. Scand.*, vol. 44, no. 2, pp. 138–145, Nov. 1958.

[49] T. Agishi, J. Temples, and E. C. Peirce 2nd, "Electrical stimulation of the carotid sinus nerve as an experimental treatment of hypertension," *J. Surg. Res.*, vol. 9, no. 5, pp. 305–309, May 1969.

[50] A. N. Brest, L. Wiener, and B. Bachrach, "Bilateral carotid sinus nerve stimulation in the treatment of hypertension," *Amer. J. Cardiol.*, vol. 29, no. 6, pp. 821–825, Jun. 1972.

[51] F. Solti, Z. Szabó, G. Kerkovits, G. Budai, E. Bodor, and I. Kalmár, "Baropacing of the carotid sinus nerve for treatment of "Intractable" hypertension," *Z. Kardiol.*, vol. 64, no. 4, pp. 368–374, Apr. 1975.

[52] T. E. Lohmeier, E. D. Irwin, M. A. Rossing, D. J. Serdar, and R. S. Kieval, "Prolonged activation of the baroreflex produces sustained hypotension," *Hypertension*, vol. 43, no. 2, pp. 306–311, Feb. 2004.

[53] T. E. Lohmeier, T. M. Dwyer, D. A. Hildebrandt, E. D. Irwin, M. A. Rossing, D. J. Serdar, and R. S. Kieval, "Influence of prolonged baroreflex activation on arterial pressure in angiotensin hypertension," *Hypertension*, vol. 46, no. 5, pp. 1194–200, Nov. 2005.

[54] T. E. Lohmeier, A. M. Barrett, and E. D. Irwin, "Prolonged activation of the baroreflex: A viable approach for the treatment of hypertension?," *Curr. Hypertens. Rep.*, vol. 7, no. 3, pp. 193–198, Jun. 2005.

[55] T. E. Lohmeier, D. A. Hildebrandt, T. M. Dwyer, A. M. Barrett, E. D. Irwin, M. A. Rossing, and R. S. Kieval, "Renal denervation does not abolish sustained baroreflex-mediated reductions in arterial pressure," *Hypertension*, vol. 49, no. 2, pp. 373–379, Feb. 2007.

[56] T. E. Lohmeier, T. M. Dwyer, E. D. Irwin, M. A. Rossing, and R. S. Kieval, "Prolonged activation of the baroreflex abolishes obesity-induced hypertension," *Hypertension*, vol. 49, no. 6, pp. 1307–1314, Jun. 2007.

[57] T. E. Lohmeier, D. A. Hildebrandt, T. M. Dwyer, R. Iliescu, E. D. Irwin, A. W. Cates, and M. A. Rossing, "Prolonged activation of the baroreflex decreases arterial pressure even during chronic adrenergic blockade," *Hypertension*, vol. 53, no. 5, pp. 833–838, May 2009.

[58] T. N. Thrasher, "Unloading arterial baroreceptors causes neurogenic hypertension," *Amer. J. Physiol.*, vol. 282, no. 4, pp. R1044–R1053, Apr. 2002.

[59] T. N. Thrasher, "Baroreceptors and the long-term control of blood pressure," *Exp. Physiol.*, vol. 89, no. 4, pp. 331–335, Jul. 2004.

[60] C. J. Dickinson, "Re: Baroreceptors and the long-term control of blood pressure," *Exp. Physiol.*, vol. 89, no. 4, pp. 335–337, Jul. 2004.

[61] P. Sleight, "Arterial baroreflexes can determine long-term blood pressure. Baroreceptors and hypertension: Time for a re-think?," *Exp. Physiol.*, vol. 89, no. 4, pp. 337–341, Jul. 2004.

[62] T. N. Thrasher, "Effects of chronic baroreceptor unloading on blood pressure in the dog," *Amer. J. Physiol.*, vol. 288, no. 4, pp. R863–R871, Apr. 2005.

[63] T. N. Thrasher, "Baroreceptors, baroreceptor unloading, and the long-term control of blood pressure," *Amer. J. Physiol.*, vol. 288, no. 4, pp. R819–R827, Apr. 2005.

[64] T. N. Thrasher, "Arterial baroreceptor input contributes to long-term control of blood pressure," *Curr. Hypertens. Rep.*, vol. 8, no. 3, pp. 249–254, Jun. 2006.

[65] P. A. Munch, M. C. Andresen, and A. M. Brown, "Rapid resetting of aortic baroreceptors in vitro," *Amer. J. Physiol.*, vol. 244, no. 5, pp. H672–H680, May 1983.

[66] H. R. Warner, "The frequency-dependent nature of blood pressure regulation by the carotid sinus studied with an electric analog," *Circ. Res.*, vol. 6, no. 1, pp. 35–40, Jan. 1958.

[67] D. Michikami, A. Kamiya, T. Kawada, M. Inagaki, T. Shishido, K. Yamamoto, H. Ariumi, S. Iwase, J. Sugenoya, K. Sunagawa, and M. Sugimachi, "Short-term electroacupuncture at Zusanli resets the arterial baroreflex neural arc toward lower sympathetic nerve activity," *Amer. J. Physiol.*, vol. 291, no. 1, pp. H318–H326, Jul. 2006.

[68] M. Sugimachi, T. Kawada, H. Yamamoto, A. Kamiya, T. Miyamoto, and K. Sunagawa, "Modification of autonomic balance by electrical acupuncture does not affect baroreflex dynamic characteristics," in *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, 2008, vol. 2008, pp. 1981–1984.

[69] T. Kawada, S. Shimizu, H. Yamamoto, T. Shishido, A. Kamiya, T. Miyamoto, K. Sunagawa, and M. Sugimachi, "Servo-controlled hind-limb electrical stimulation for short-term arterial pressure control," *Circ. J.*, vol. 73, no. 5, pp. 851–859, May 2009.

[70] H. Yamamoto, T. Kawada, A. Kamiya, T. Kita, and M. Sugimachi, "Electroacupuncture changes the relationship between cardiac and renal sympathetic nerve activities in anesthetized cats," *Auton. Neurosci.*, vol. 144, no. 1-2, pp. 43–49, Dec. 2008.

[71] Y. Yanagiya, T. Sato, T. Kawada, M. Inagaki, T. Tatewaki, C. Zheng, A. Kamiya, H. Takaki, M. Sugimachi, and K. Sunagawa, "Bionic epidural stimulation restores arterial pressure regulation during orthostasis," *J. Appl. Physiol.*, vol. 97, no. 3, pp. 984–990, Sep. 2004.

[72] F. Yamasaki, T. Ushida, T. Yokoyama, M. Ando, K. Yamashita, and T. Sato, "Artificial baroreflex: Clinical application of a bionic baroreflex system," *Circulation*, vol. 113, no. 5, pp. 634–639, Feb. 2006.

[73] K. Yamamoto, T. Kawada, A. Kamiya, H. Takaki, T. Shishido, K. Sunagawa, and M. Sugimachi, "Muscle mechanoreflex augments arterial baroreflex-mediated dynamic sympathetic response to carotid sinus pressure," *Amer. J. Physiol.*, vol. 295, no. 3, pp. H1081–H1089, Sep. 2008.

[74] K. Yamamoto, T. Kawada, A. Kamiya, H. Takaki, M. Sugimachi, and K. Sunagawa, "Static interaction between muscle mechanoreflex and arterial baroreflex in determining efferent sympathetic nerve activity," *Amer. J. Physiol.*, vol. 289, no. 4, pp. H1604–H1609, Oct. 2005.

[75] K. Yamamoto, T. Kawada, A. Kamiya, H. Takaki, T. Miyamoto, M. Sugimachi, and K. Sunagawa, "Muscle mechanoreflex induces the pressor response by resetting the arterial baroreflex neural arc," *Amer. J. Physiol.*, vol. 286, no. 4, pp. H1382–H1388, Apr. 2004.

[76] M. Yoshida, Y. Murayama, A. Chishaki, and K. Sunagawa, "Noninvasive transcutaneous bionic baroreflex system prevents severe orthostatic hypotension in patients with spinal cord injury," in *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, 2008, vol. 2008, pp. 1985–1987.

[77] J. N. Townend and W. A. Littler, "Cardiac vagal activity: A target for intervention in heart disease," *Lancet*, vol. 345, no. 8955, pp. 937–938, Apr. 1995.

[78] M. Li, C. Zheng, T. Sato, T. Kawada, M. Sugimachi, and K. Sunagawa, "Vagal nerve stimulation markedly improves long-term survival after chronic heart failure in rats," *Circulation*, vol. 109, no. 1, pp. 120–124, Jan. 2004.

[79] C. Zheng, M. Li, M. Inagaki, T. Kawada, K. Sunagawa, and M. Sugimachi, "Vagal stimulation markedly suppresses arrhythmias in conscious rats with chronic heart failure after myocardial infarction," in *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, 2005, vol. 7, pp. 7072–7075, 1.

[80] M. Li, C. Zheng, M. Inagaki, T. Kawada, K. Sunagawa, and M. Sugimachi, "Chronic vagal stimulation decreased vasopressin secretion and sodium ingestion in heart failure rats after myocardial infarction," in *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, 2005, vol. 4, pp. 3962–3965.

[81] T. Kawada, T. Yamazaki, T. Akiyama, M. Li, H. Ariumi, H. Mori, K. Sunagawa, and M. Sugimachi, "Vagal stimulation suppresses ischemia-induced myocardial interstitial norepinephrine release," *Life Sci.*, vol. 78, no. 8, pp. 882–887, Jan. 2006.

[82] T. Kawada, T. Yamazaki, T. Akiyama, H. Kitagawa, S. Shimizu, M. Mizuno, M. Li, and M. Sugimachi, "Vagal stimulation suppresses ischemia-induced myocardial interstitial myoglobin release," *Life Sci.*, vol. 83, no. 13-14, pp. 490–495, Sep. 2008.

[83] K. Uemura, M. Li, T. Tsutsumi, T. Yamazaki, T. Kawada, A. Kamiya, M. Inagaki, K. Sunagawa, and M. Sugimachi, "Efferent vagal nerve stimulation induces tissue inhibitor of metalloproteinase-1 in myocardial ischemia-reperfusion injury in rabbit," *Amer. J. Physiol.*, vol. 293, no. 4, pp. H2254–H2261, Oct. 2007.

[84] L. V. Borovikova, S. Ivanova, M. Zhang, H. Yang, G. I. Botchkina, L. R. Watkins, H. Wang, N. Abumrad, J. W. Eaton, and K. J. Tracey, "Vagus nerve stimulation attenuates the systemic inflammatory response to endotoxin," *Nature*, vol. 405, no. 6785, pp. 458–462, May 2000.

[85] K. J. Tracey, "The inflammatory reflex," *Nature*, vol. 420, no. 6917, pp. 853–859, Dec. 2002.

[86] H. Wang, M. Yu, M. Ochani, C. A. Amella, M. Tanovic, S. Susarla, J. H. Li, H. Wang, H. Yang, L. Ulloa, Y. Al-Abed, C. J. Czura, and K. J. Tracey, "Nicotinic acetylcholine receptor alpha7 subunit is an essential regulator of inflammation," *Nature*, vol. 421, no. 6821, pp. 384–388, Jan. 2003.

[87] K. J. Tracey and H. S. Warren, "Human genetics: An inflammatory issue," *Nature*, vol. 429, no. 6987, pp. 35–37, May 2004.

[88] J. Springer, D. O. Okonko, and S. D. Anker, "Vagal nerve stimulation in chronic heart failure: An antiinflammatory intervention?," *Circulation*, vol. 110, no. 4, p. e34, Jul. 2004.

[89] S. Guarini, D. Altavilla, M. M. Cainazzo, D. Giuliani, A. Bigiani, H. Marini, G. Squadrito, L. Minutoli, A. Bertolini, R. Marini, E. B. Adamo, F. S. Venuti, and F. Squadrito, "Efferent vagal fibre stimulation blunts nuclear factor-kappaB activation and protects against hypovolemic hemorrhagic shock," *Circulation*, vol. 107, no. 8, pp. 1189–1194, Mar. 2003.

[90] G. M. De Ferrari, A. Sanzo, H. J. G. M. Crijns, R. Dennert, G. Milasinovic, S. Raspopovic, M. Borggrefe, C. Wolpert, J. Kuschyk, A. Schoene, H. Klein, J. Smid, A. Gavazzi, M. Zabel, and P. J. Schwartz, *Chronic Vagus Nerve Stimulation: A New Treatment Modality for Congestive Heart Failure*. Orlando, FL: American College of Cardiology, 2009.

[91] I. H. Zucker, J. F. Hackley, K. G. Cornish, B. A. Hiser, N. R. Anderson, R. Kieval, E. D. Irwin, D. J. Serdar, J. D. Peuler, and M. A. Rossing, "Chronic baroreceptor activation enhances survival in dogs with pacing-induced heart failure," *Hypertension*, vol. 50, no. 5, pp. 904–910, Nov. 2007.

[92] G. I. Voss, P. G. Katona, and H. J. Chizeck, "Adaptive multivariable drug delivery: Control of arterial pressure and cardiac output in anesthetized dogs," *IEEE Trans. Biomed. Eng.*, vol. BE-34, pp. 617–623, Aug. 1987.

[93] C. Yu, P. J. Roy, H. Kaufman, and B. W. Bequette, "Multiple-model adaptive predictive control of mean arterial pressure and cardiac output," *IEEE Trans. Biomed. Eng.*, vol. 39, pp. 765–778, Aug. 1992.
[94] K. Uemura, M. Sugimachi, T. Kawada, A. Kamiya, Y. Jin, K. Kashihara, and K. Sunagawa, "A novel framework of circulatory equilibrium," *Amer. J. Physiol.*, vol. 286, no. 6, pp. H2376–H2385, Jun. 2004.
[95] A. C. Guyton, A. W. Lindsey, B. Abernathy, and T. Richardson, "Venous return at various right atrial pressures and the normal venous return curves," *Amer. J. Physiol.*, vol. 189, no. 3, pp. 609–615, Jun. 1957.
[96] K. Sagawa, L. Maughan, H. Suga, and K. Sunagawa, *Cardiac Contraction and the Pressure-Volume Relationship.* New York: Oxford Univ. Press, 1988, ch. 5, pp. 232–298.
[97] K. Uemura, T. Kawada, A. Kamiya, T. Aiba, I. Hidaka, K. Sunagawa, and M. Sugimachi, "Prediction of circulatory equilibrium in response to changes in stressed blood volume," *Amer. J. Physiol.*, vol. 289, no. 1, pp. H301–H307, Jul. 2005.
[98] K. Uemura, A. Kamiya, I. Hidaka, T. Kawada, S. Shimizu, T. Shishido, M. Yoshizawa, M. Sugimachi, and K. Sunagawa, "Automated drug delivery system to control systemic arterial pressure, cardiac output, and left heart filling pressure in acute decompensated heart failure," *J. Appl. Physiol.*, vol. 100, no. 4, pp. 1278–1286, Apr. 2006.
[99] K. Uemura, K. Sunagawa, and M. Sugimachi, "Computationally managed bradycardia improved cardiac energetics while restoring normal hemodynamics in heart failure," *Ann. Biomed. Eng.*, vol. 37, no. 1, pp. 82–93, Jan. 2009.
[100] K. Hayashida, K. Sunagawa, M. Noma, M. Sugimachi, H. Ando, and M. Nakamura, "Mechanical matching of the left ventricle with the arterial system in exercising dogs," *Circ. Res.*, vol. 71, no. 3, pp. 481–489, Sep. 1992.
[101] M. Sugimachi, K. Todaka, K. Sunagawa, and M. Nakamura, "Optimal afterload for the heart vs. optimal heart for the afterload," *Front. Med. Biol. Eng.*, vol. 2, no. 3, pp. 217–221, 1990.

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Wireless Pers Commun
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An Analysis of Interference Mitigation Capability of Low Duty-Cycle UWB Communications in the Presence of Wideband OFDM System

Keisuke Sodeyama · Koji Ishibashi · Ryuji Kohno

Abstract Low duty-cycle (LDC) algorithm is interference mitigation technique, which can reduce the average interference to the existing radio systems by lowering pulse repetition interval or pulse occupation time. In this paper, the coexistence environment between low data rate ultra wideband (UWB) communication system such as wireless sensor network and the existing wideband system using orthogonal frequency division multiplexing (OFDM) such as 4th generation mobile cellular system (4G), worldwide interoperability for microwave access (WiMAX), and field pickup unit (FPU) is considered. In order to analyze the interference mitigation capability of LDC algorithm with impulse based UWB (LDC-UWB) system, the frame error rate (FER) of wideband OFDM system is examined for two types of LDC-UWB system: the signal with random polarity such as binary pole signals and without random polarity such as mono pole signals. We present that LDC algorithm is an efficient interference mitigation technique for low data rate UWB communication via computer simulations regardless of definitions of transmitted energy of UWB communication system, and also that the signal with random polarity is suitable for LDC-UWB system to mitigate interference to the other radio systems. We further investigate the adequate duty-cycle of LDC-UWB system for each definition of transmitted power of UWB communication.

Keywords Low duty-cycle · LDC-UWB · Interference mitigation technique · Wideband OFDM system

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1 Introduction

As increasing wireless applications and the quantity of digital information, more efficient digital communications are highly required. Thus, some new technologies such as ultra wideband (UWB) communication systems have been proposed for short-range wireless applications [1,2]. UWB communication has also gained much attention as coexistence with other radio systems because of its low power spectrum density equivalent to noise level. The potential applications of UWB communication include high data rate wireless personal area network (WPAN) which can achieve more than 100 Mbps over short distance and wireless sensor networks such as IEEE 802.15.4a providing low data rate UWB communication over medium range combined with precise ranging and positioning capabilities. Thus, UWB communication is a promised technology to apply various application. While wireless local area network (WLAN) and Bluetooth coexist each other and also with the other unlicensed systems in the industry, science, and medical (ISM) band which is opened for some applications in Japan, UWB communication coexist with licensed system such as worldwide interoperability for microwave access (WiMAX), 4th generation mobile cellular systems (4G), and field pickup unit (FPU). Therefore, UWB communication may inherently degrade the performance of the existing other radio systems since the radio band of the UWB communication systems overlaps that of the other radio systems such as WiMAX, 4G, and FPU. The technical conditions on the usage of UWB communication system were set up by the Ministry of Internal Affairs and Communications on March 2006, in Japan [3] and it is imperative for UWB communications to equip the interference mitigation techniques, *detect and avoid* (DAA) [4–15] and *low duty-cycle* (LDC) [16–20].

In general, DAA technique aims to mainly at high data rate UWB communication such as WPAN. The device with DAA can detect the signals from other radio systems and avoid interference to them. Although UWB communication systems with DAA technique are allowed to transmit with power level of −41.25 dBm/MHz, those without DAA technique must limit their emission level by −70 dBm/MHz which is lower than the noise level. Namely, unless interference mitigation techniques are adopted, the emission level of UWB signals is 30 dB lower than FCC UWB indoor environment spectral mask to meet the current regulation in Japan. High data rate UWB communication with DAA techniques have been studied in the literature [4–8]. DAA techniques are divided into three types: frequency domain DAA [9–12], time domain DAA [13,14] and space domain DAA [15]. For frequency domain DAA techniques the UWB devices detect the radio frequency band of the other existing radio system and avoid interference to these system by using frequency hopping, transmit power control, frequency filter and so on [9–12]. UWB communication system with time domain DAA techniques, which are very similar to carrier sense multiple access with collision avoidance (CSMA/CA) sense the existing radio systems before establishing data communication link [13,14]. Space domain DAA technique have been proposed that UWB communication systems can mitigate the interference to the existing radio systems by using spatial beam-forming of array antennas [15].

On the other hand, LDC algorithm mainly aims to low data rate UWB communications such as IEEE 802.15.4a [16]. IEEE 802.15.4a standard for low data rate sensor networks is designed for long battery life, low cost, and low latency rather than maximizing the data rate. Thus, DAA technique may not be suited for low data rate UWB communication because of their strict constraints on energy consumption and costs. Therefore, LDC algorithm can be an attractive candidate for interference mitigation in low data rate UWB communications.

The aim of LDC algorithm is to reduce the average interference to the existing radio systems by lowering pulse repetition interval or pulse occupation time. The features of LDC

algorithm imposes low data rate but achieve low energy consumption since the pulse repetition interval is extended. Originally, LDC algorithm has been proposed to reduce energy consumption [17]. Moreover, in UWB ad-hoc network, LDC algorithm has been studied to improve the near/far power disparities or pulse-on-pulse interference of multiple access [18,19]. Furthermore, in low power low rate UWB communication, LDC algorithm has been studied to improve the protocol design of medium access control (MAC) layer [20].

However, the design of the duty-cycle of impulse-based UWB communication system with LDC algorithm (LDC-UWB) has not been presented. In addition, despite all the benefits inherent to LDC algorithm, UWB communication systems still interfere with the existing other radio systems. In this paper, we focus on the coexistence environment between LDC-UWB system and wideband system based on orthogonal frequency division multiplexing (OFDM) such as 4G, WiMAX, and FPU. This paper analyzes the performance of UWB system with LDC algorithm as the interference mitigation technique in the presence of coexistence environment. In order to analyze the interference mitigation capability of LDC-UWB, the performance of wideband OFDM systems based on the frame error rate (FER) over the coexistence environment is presented via computer simulations of C language. Moreover, two types of LDC-UWB signal interference are considered: the signal with random polarity such as binary pole signals and without random polarity such as mono pole signals. We present that LDC algorithm is an efficient interference mitigation technique for low data rate UWB communication. In addition, the definition of UWB transmission power has been approached in two different manners: fixed power per pulse and fixed power per unit of time. The question that may arise at this point is how to design the duty-cycle of LDC-UWB system by each definition of UWB transmission power. Therefore, we further investigate the adequate duty-cycle of LDC-UWB system for each definition.

The rest of this paper is organized as follows. Section 2 describes the LDC-UWB system model considered throughout this paper. The wideband OFDM system model is presented in Sect. 3. The simulation results are presented in Sect. 4. Finally, the conclusions are drawn in Sect. 5.

2 LDC-UWB System Model

The major parameters of UWB communication systems are given in Table 1. In this paper, low data rate UWB communication system is considered such as wireless sensor network, and thus, its data rate is below 1 MHz bits per second (bps). Also, the pulse repetition frequency (PRF) is given as 3.9 or 15.6 MHz, which is compliant with IEEE 802.15.4a. Also, PRF is defined as the number of the pulse in one frame of the transmit slot of LDC-UWB device.

Moreover, two types of LDC-UWB signal interference are considered: with random polarity such as binary pole signals and without random polarity such as mono pole signals. The reason for the later is the significant simplicity of the circuit design when using the signal without random polarity. We also consider two definitions of LDC-UWB transmission power: fixed power per pulse and fixed power per unit of time since these definitions have been discussed at the mutual interference between pulse-based UWB system and other radio system.

2.1 Specifications of LDC-UWB System

In this protocol, every UWB communication devices only wake up for short time to communicate with each other and timing schedule for communication is not available at each device.

Table 1 Major parameters of LDC-UWB systems

Type of UWB system	Impulse based UWB
Center frequency: f_c	4.0 GHz
Bandwidth	2 GHz
Data rate	> 1 Mbps
Pulse repetition frequency (PRF)	3.9 MHz, 15.6 MHz
Pulse width	0.5 ns
Duty-cycle: DC	0.1, 0.5, 1, 10, 50, 100%
Tx (or Rx) slot length	1–1,001 ms
Sleep period after Tx (or Rx)	1,000–0 ms
Frame length of LDC-UWB system	2,002 ms

Thus, in order to establish a communication link, access controller (AC) is introduced. The wireless network based on LDC protocol must have one AC device, which may be allowed relatively high power consumption and high duty-cycle (HDC) compared with those of non-AC devices. AC can receive messages from all UWB devices belonging to its own network besides having AC has the timing schedule of every UWB devices. Note that this protocol is suitable for indoor applications since AC device should be connected to the power supply because of its high power consumption and high duty-cycle. Figure 1 illustrates an example of the LDC protocol with UWB devices A and B, where, the duty-cycle is about 0.1% with both UWB devices transmit (Tx) and receive (Rx) time slot length of 1 ms. AC has 2,002 ms receive time slot and the duty-cycle of LDC-UWB system is defined as

$$\mathrm{DC} = \frac{2T_s}{T_f}, \tag{1}$$

where DC is the duty-cycle of LDC-UWB, T_s is the Tx + Rx slot length, T_f is the frame length of LDC-UWB (T_f is fixed 2,002 ms). As example, duty-cycle 0.1% is defined that Tx and Rx of UWB communication devices are 1 ms, respectively, and total sleep period per frame is 2,000 ms, duty-cycle 50% is defined that Tx and Rx are 500 ms and total sleep period per frame is 1,002 ms.

The maximal number of interference pulse N_p is defined as

$$N_p = L_{Tx} \times \mathrm{DC} \times f_{PRF}, \tag{2}$$

where L_{Tx} is the transmission frame length of LDC-UWB, DC is the duty-cycle of LDC-UWB system and f_{PRF} is the PRF of LDC-UWB system.

Device A keeps on sending a communication request (Comm. Req.) message to AC including its own timing schedule and a request to communicate with device B until the Ack message received from AC. Simultaneously, device B keeps on sending a Query message until Replay message from AC device is received as illustrated in Fig. 1, where Replay message includes the timing schedule of device A and its request to communicate with device B. Then, device B adjusts its own timing schedule to that of device A and device B sends a Ready message to device A directly. Then, a communication link between devices A and B is established.

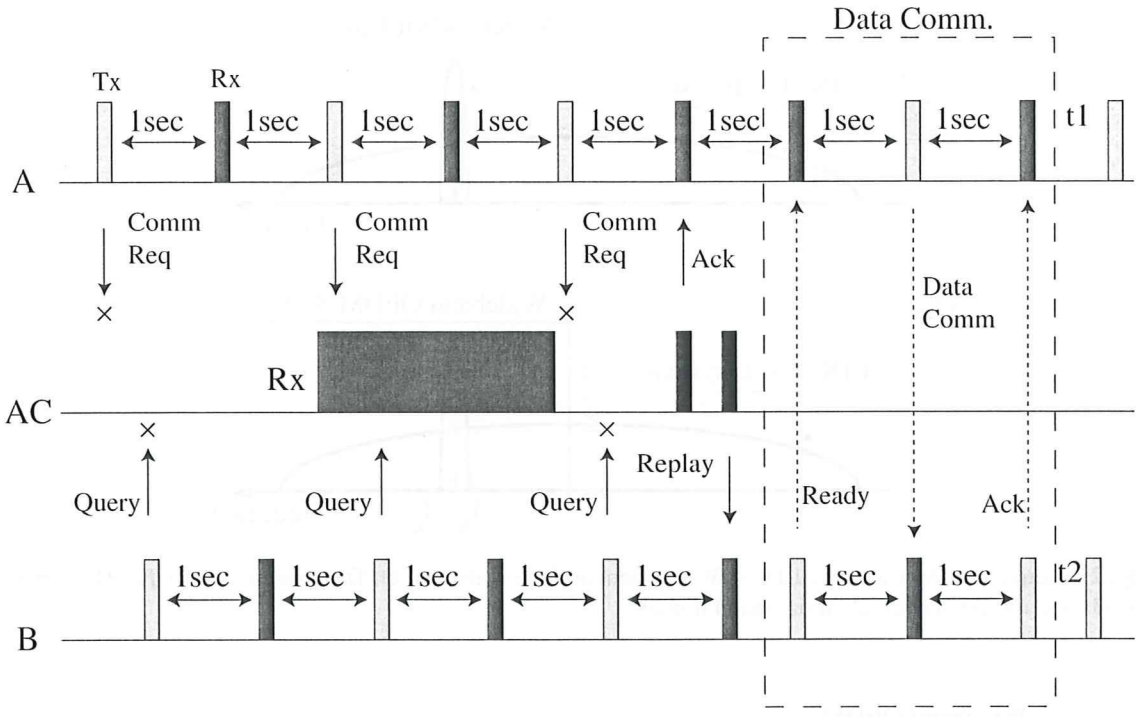

Fig. 1 an example of the LDC protocol with UWB communication devices A and B, where the duty-cycle is about 0.1%

2.2 Modified Equivalent Baseband UWB System

In this paper, UWB signal interference is modeled a modified equivalent baseband system [21]. UWB communication is permitted in Japan at the radio frequency from 3.4 to 4.8 GHz and from 7.25 to 10.25 GHz. At these frequencies, computer simulation are extremes time consuming owing to the high sampling frequency. Therefore, the simulation model implemented a modified equivalent baseband system in order to speed up the simulation. Figure 2 illustrates the spectral relation between the culprit LDC-UWB system and the wideband OFDM system, whose center frequencies are f_c and f_v, respectively, in the radio frequency (RF) domain. The wideband OFDM system is shifted from f_v to $f_v - f_c$ in order to tune the center frequency to specific frequency of the UWB signal in the modified equivalent baseband domain.

3 Wideband OFDM System Model

Wideband OFDM systems are considered among the most appropriate schemes for future high data rate communications systems due to their effective bandwidth utilization and the simplicity of the equalization strategies needed to compensate the channel frequency selective fading. The OFDM technique has been adopted in several standards, e.g., digital audio broadcasting (DAB), digital video broadcasting (DVB), multimedia mobile access communications (MMAC) and WLAN. It also has been proposed for cable TV, broadband radio access networks, multi-user communications via satellite link, WiMAX, 4G and FPU.

In this paper, we focus on the coexistence environment of UWB communication systems and wideband OFDM systems such as 4G and WiMAX. The basic idea of OFDM is to divide the available spectrum into several sub-channels (sub-carriers). By making all sub-channels

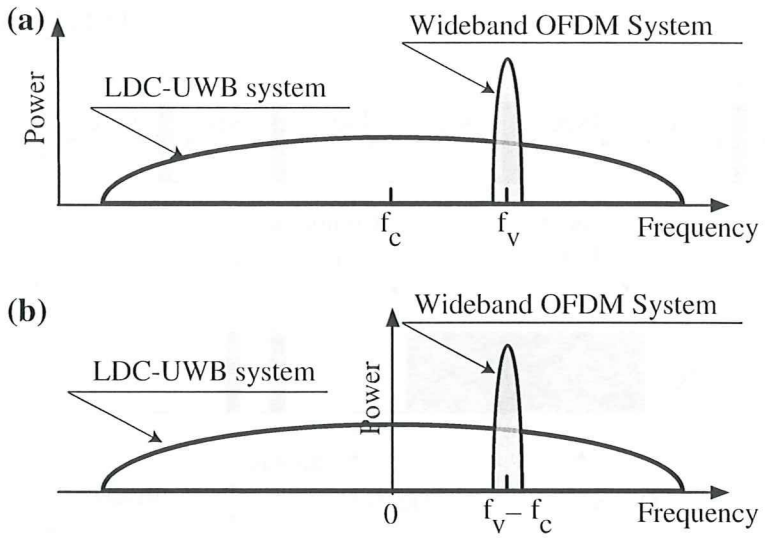

Fig. 2 Frequency spectra of the LDC-UWB system and the wideband OFDM system in: (**a**) the RF domain and (**b**) the modified equivalent baseband domain

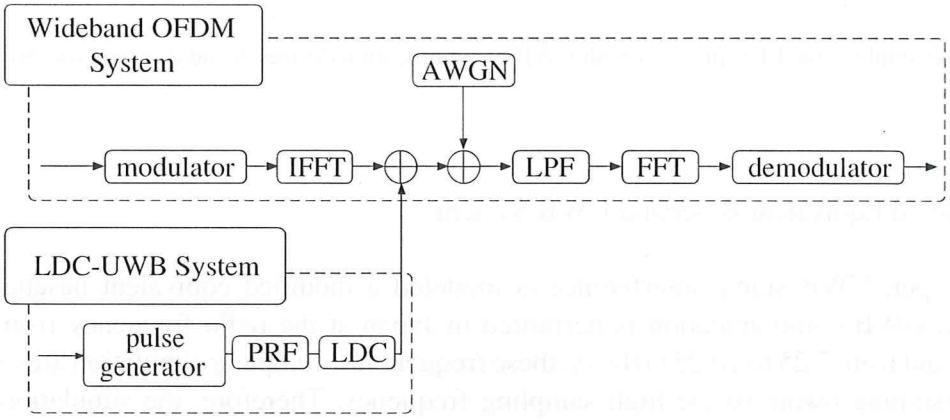

Fig. 3 The block diagram of the wideband OFDM system

narrower than the coherence bandwidth of the radio channels, they experience almost flat fading, simplifying the equalization process (one tap equalizer). In order to obtain a high spectral efficiency the sub-channels are overlapping, still keeping the orthogonality of their sub-carriers. This orthogonality is completely maintained, even when the signal passes through a time dispersive channel by introducing a cyclic prefix (the last part of the OFDM symbol is copied in front of the transmitted symbol). This of course introduces a loss in signal-to-noise ratio (SNR), but if the impulse response of channel is shorter than the cyclic prefix, then the inter-symbol interference (ISI) and inter-carrier interference (ICI) are completely removed at the output of the channel [22].

Figure 3 shows the block diagram of the wideband OFDM system. Major parameters of the wideband OFDM systems are listed in Table 2 (c.f., [23]). In this paper, the bandwidth of the wideband OFDM system is about 100 MHz and, thus, its data rate is 100 MHz bps. The equivalent baseband model is employed, therefore, the interference of the UWB signals is introduced by adding the UWB signal to the transmitted OFDM signal (see Fig. 3). After that, the received signals are passed through the low pass filter (LPF) of the wideband OFDM system.

Table 2 Major parameters of the wideband OFDM systems

Bandwidth	101.5 MHz
Data rate objective	>100 Mbits/s
Number of sub-carriers: N_c	768
Sub-carrier spacing: F_s	131.8 kHz
OFDM symbol duration: T_s	7.585 μs
Total OFDM symbols duration: T_s'	9.259 μs
Number of OFDM symbols per frame: N_s	54
OFDM frame length: T_{fr}	500 μs
Symbol mapping	QPSK

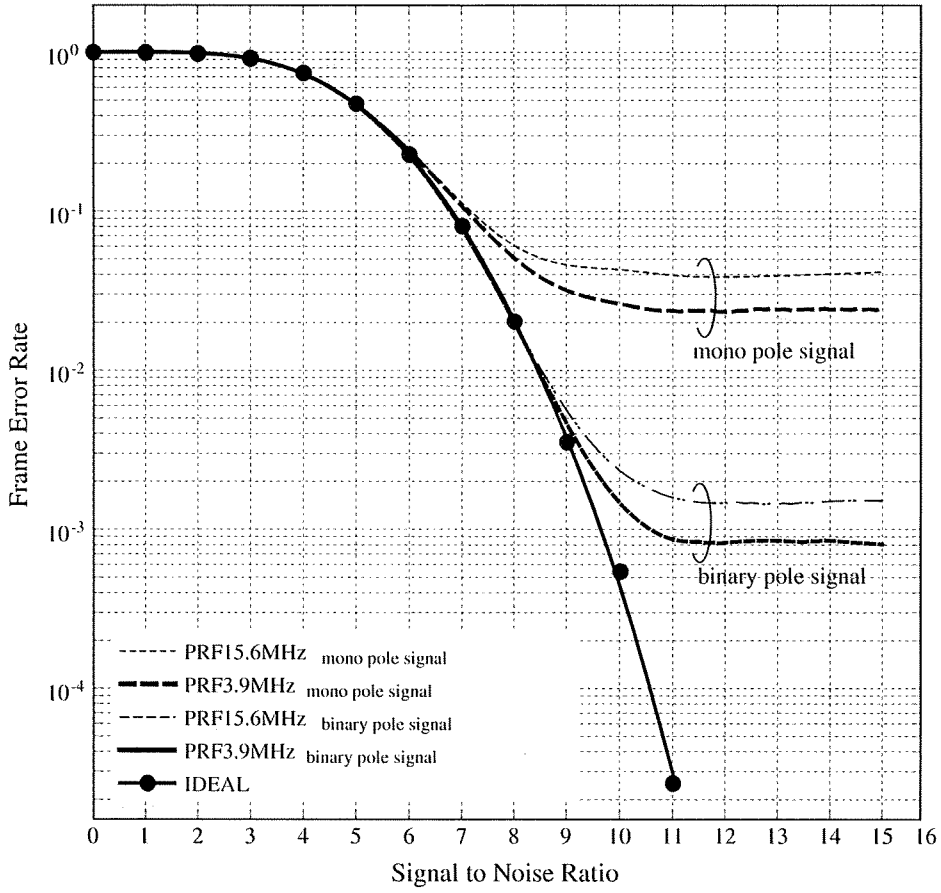

Fig. 4 The FER of the wideband OFDM system over AWGN channel with the interference by LDC-UWB system when SIR = 10 dB and duty-cycle = 0.1%. The definition of UWB transmission power is fixed power per pulse

4 Simulation Results

Although LDC protocol promises that the average interference to the wideband OFDM systems can be suppressed, LDC-UWB communication systems still interfere to wideband OFDM systems even with LDC protocol. Moreover, when UWB communication devices (or users) are increased, the interference to wideband OFDM system may be increased even applying lower duty-cycle.

First, the FER of the wideband OFDM systems over additive white Gaussian (AWGN) channel with the interference by the LDC-UWB system is analyzed. Figure 4 shows the FER

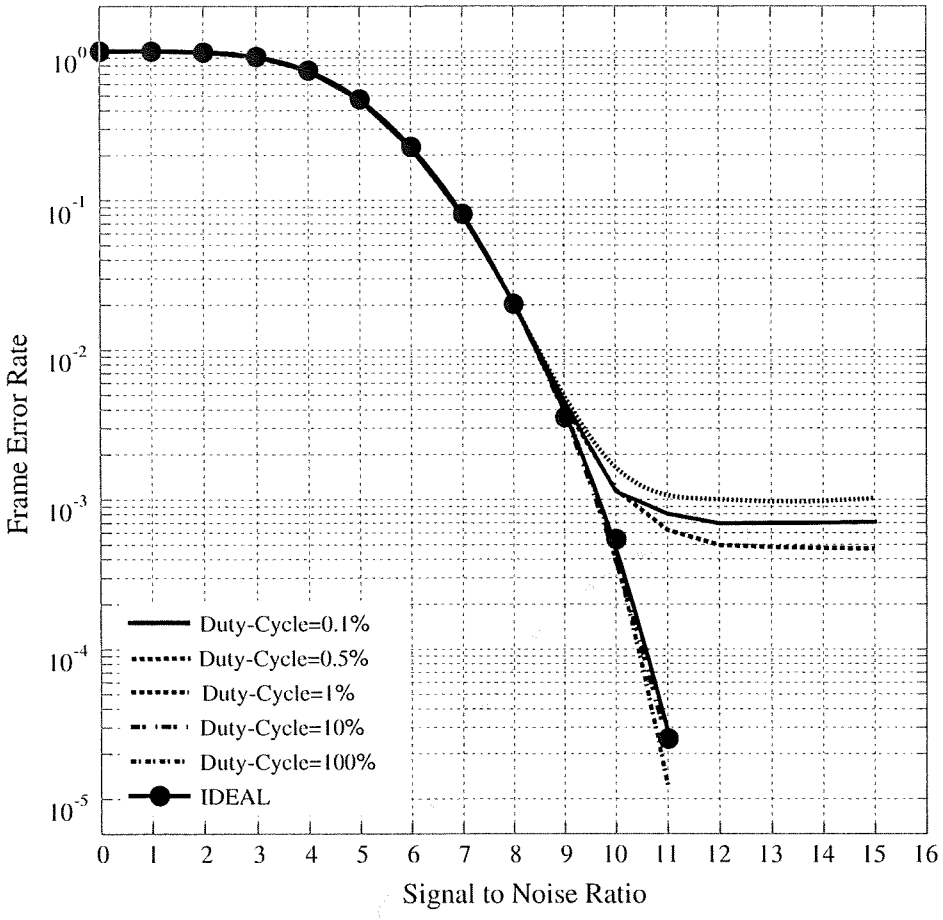

Fig. 5 The FER of the wideband OFDM systems over AWGN channel with the interference by LDC-UWB system when SIR = 10 dB and PRF = 3.9 MHz. The definition of UWB transmission power is fixed power per unit of time

of the wideband OFDM system with the interference by LDC-UWB system when signal to interference ratio (SIR) = 10 dB, duty-cycle is 0.1% and PRF is given as 3.9 or 15.9 MHz. Also, SIR is defined as the wideband OFDM system transmission power to LDC-UWB interference transmission power ratio. LDC-UWB transmission power is fixed power per pulse.

From Fig. 4, the FER of the wideband OFDM system with interference by binary pole signals is superior to the interference by mono pole signals. The reason for this to occur is that the LDC-UWB interference by mono pole signals amplifies the interference since the constant signal polarity adds to wideband OFDM system. Meanwhile, the interference by binary pole signal is reduced by the each random polarity of LDC-UWB signals. Therefore, LDC-UWB signal needs the random polarity such as binary pole signal. In other words, the binary pole signal is essential for LDC-UWB signal to reduce interference to wideband OFDM systems.

From another viewpoint, the FER of wideband OFDM systems are degraded by increasing PRF of LDC-UWB systems since the number of interference pulses are increased. Therefore, the PRF of LDC-UWB systems should be carefully chosen in consideration of the quality of performance required by wideband OFDM system and by each LDC-UWB application.

When the definition of LDC-UWB transmission power is fixed, the power per unit of time, the FER of wideband OFDM system with interference by LDC-UWB system with SIR = 10 dB, and PRF = 3.9 MHz is presented in Fig. 5. Figure 6 shows the performance when PRF is changed to 15.6 MHz.

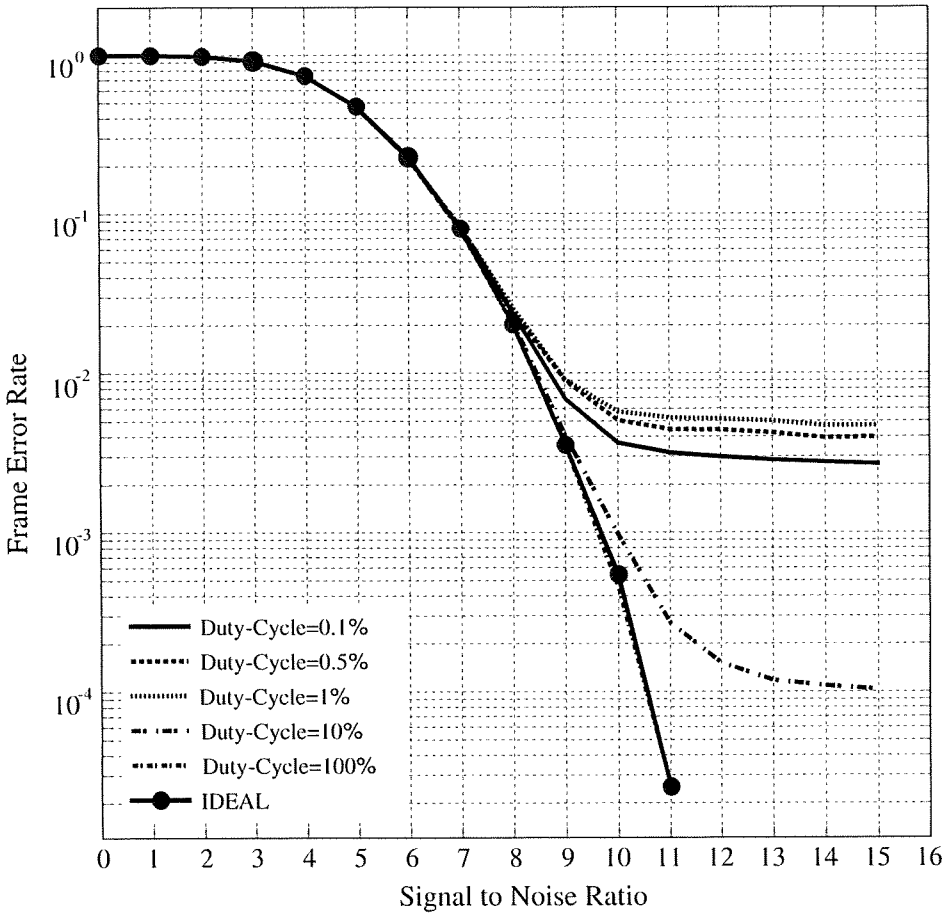

Fig. 6 The FER of the wideband OFDM systems over AWGN channel with the interference by LDC-UWB system when SIR = 10 dB and PRF = 15.6 MHz. The definition of UWB transmission power is fixed power per unit of time

From Figs. 5 and 6, when the definition of UWB transmission power is fixed power per unit of time, the FER of wideband OFDM systems is superior to that of fixed power per pulse since the transmission power of each pulses is reduced. Therefore, the collision probability considered, the interference of LDC-UWB system is improved as longer as duty-cycle. However, the communication area of LDC-UWB devices is narrowed since the signal power is reduced by increasing duty-cycle. Thus, a trade-off between the communication area of LDC-UWB devices and duty-cycle of LDC-UWB system can be found. Moreover, the FER of wideband OFDM systems are degraded by decreasing PRF of LDC-UWB systems since the power of each pulses are decreasing.

Secondly, the FER of wideband OFDM system over AWGN channel with the interference by LDC-UWB systems is presented when the duty-cycle of LDC-UWB system is changed. Here, SNR is fixed to 10 dB. The FER of the wideband OFDM systems with the interference by the LDC-UWB communication devices are shown in Fig. 7, where PRF = 3.9 MHz. Figure 8 shows the performance when PRF = 15.6 MHz. Here, the definition of LDC-UWB transmission power is fixed power the pulse.

From Figs. 7 and 8, the FER of wideband OFDM systems are degraded by increasing of the duty-cycle of LDC-UWB systems. LDC cannot suppress interference to wideband OFDM systems completely. However it can be mitigated moderately without additional complexity such as DAA. Thus, the duty-cycle of LDC-UWB should be chosen carefully in consideration of the quality of the service required by the wideband OFDM system in the physical layer.

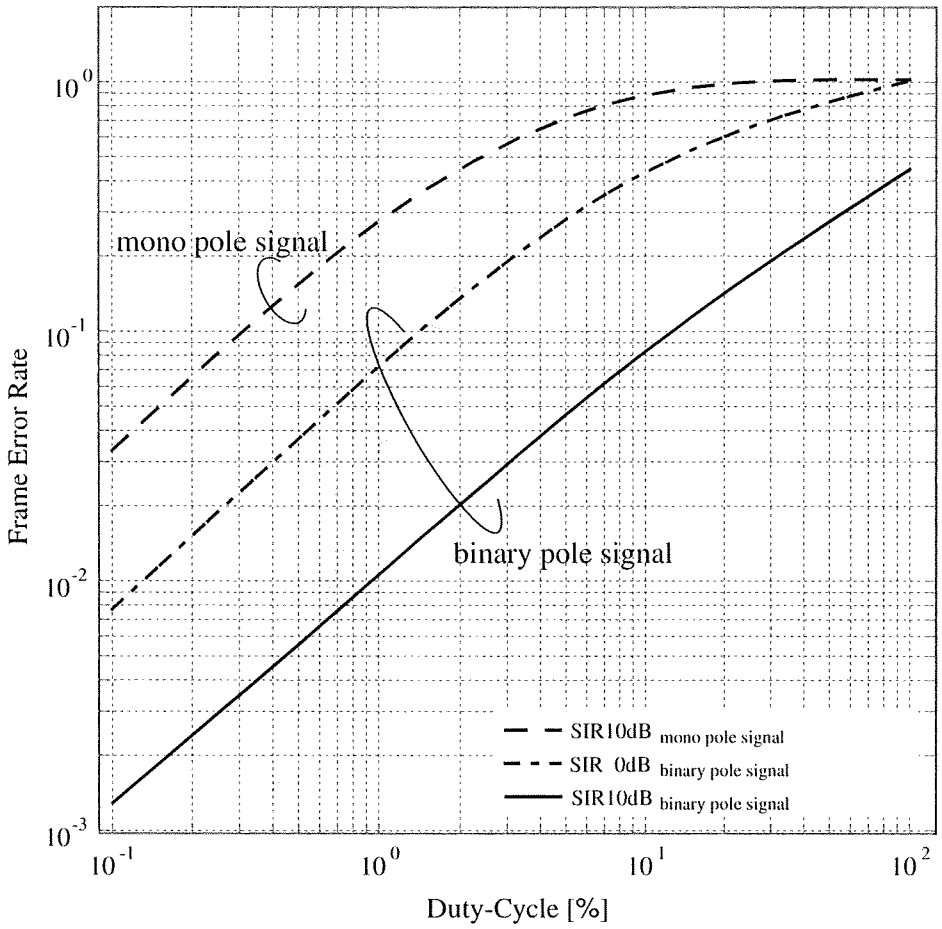

Fig. 7 The FER of the wideband OFDM system with the interference by the LDC-UWB communication devices, when SNR = 10 dB and the PRF = 3.9 MHz. The definition of UWB transmission power is fixed power per pulse

When the LDC-UWB signal power is fixed power per unit of time, the FER of wideband OFDM system with the interference by changing the duty-cycle of LDC-UWB system is presented. Here, SNR is fixed to 10 dB. Figure 9 shows the FER of the wideband OFDM systems with the interference by LDC-UWB communication devices.

In Fig. 9, the FER of wideband OFDM system with interference by duty-cycle = 100% is superior to that of duty-cycle = 0.1%. For the reason that although the collision probability between wideband OFDM system and LDC-UWB system is increased, the pulse signal power becomes lower since the number of pulses is increased. However, when the duty-cycle of DC-UWB system is increased, simultaneously, the power consumption is also grown. Therefore, in IEEE 802.15.4a, such as wireless sensor network, using duty-cycle = 100% is difficult. Therefore, the duty-cycle of LDC-UWB system should be set to distinctly low values of $<0.1\%$.

From these results, the duty-cycle of LDC-UWB system should be chosen carefully in consideration of the requirements of the each LDC-UWB applications. When the LDC-UWB signal power is fixed power per pulse, the interference to wideband OFDM is mitigated with reducing duty-cycle of LDC-UWB system. Therefore, when the LDC-UWB signal power is fixed power per pulse, the duty-cycle of LDC-UWB should be chosen low values of 0.1% and using PRF = 3.9 MHz is absolutely essential. Meanwhile, when the LDC-UWB signal power is fixed power per unit of time, the duty-cycle of LDC-UWB system is depended on both the collision probability between wideband OFDM system and LDC-UWB system

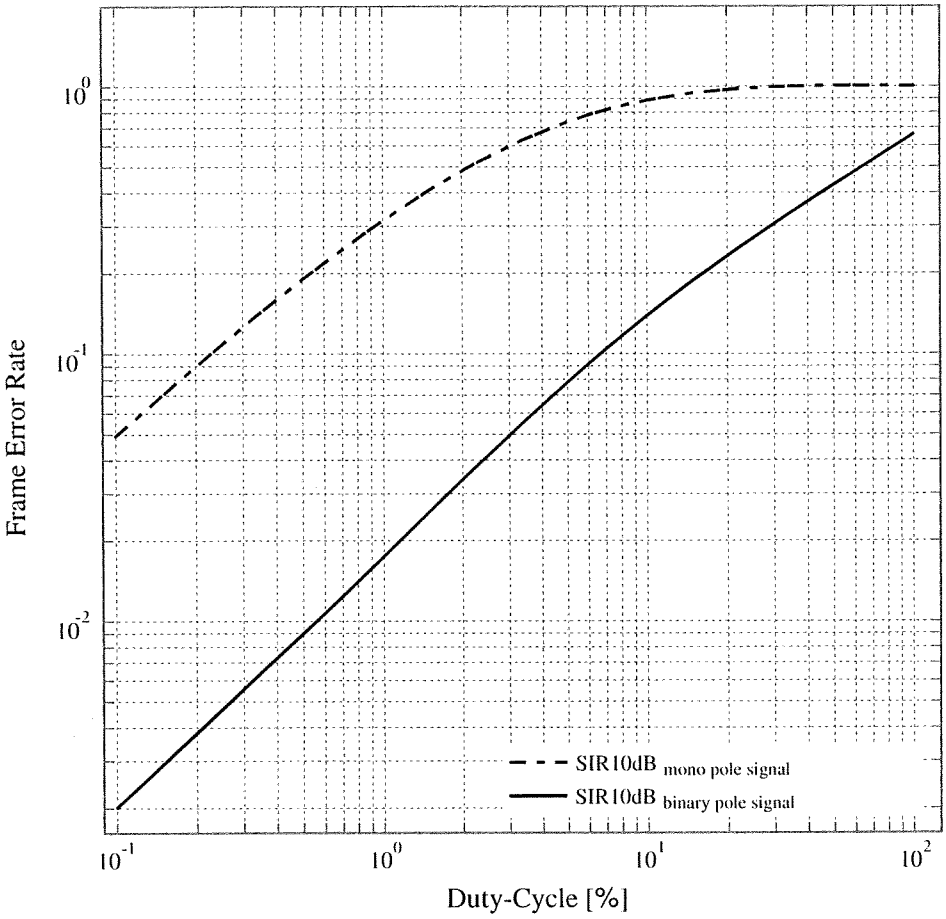

Fig. 8 The FER of the wideband OFDM system with the interference by the LDC-UWB communication devices, when SNR = 10 dB and the PRF = 15.6 MHz. The definition of UWB transmission power is fixed the power per the pulse

and the power of LDC-UWB pulse. In IEEE 802.15.4a such as wireless sensor network, using higher duty-cycle is difficult since the power consumption is also significantly high. Therefore, when the LDC-UWB signal power is fixed power per unit of time, the duty-cycle of LDC-UWB should be set to distinctly low values of $<0.1\%$ and using PRF = 15.6 MHz is absolutely essential. Thus, the design issues of PRF and duty-cycle are different with each definition of LDC-UWB transmission power.

5 Conclusions

In this paper, we have focused on the coexistence environment between LDC-UWB system and wideband OFDM system and have analyzed the interference mitigation capability of LDC-UWB system in the presence of wideband OFDM system. The performance of wideband OFDM system based on FER over the coexistence environment has been presented via computer simulations. The signal with random polarity such as binary pole signal has been necessary to mitigate the interference for wideband OFDM system. Moreover, by the definition of the UWB transmission power, the duty-cycle of LDC-UWB system has been needed to establish in consideration of the request of the each LDC-UWB application. Moreover, we have presented the design issues of PRF and duty-cycle are different with each definition of LDC-UWB transmission power.

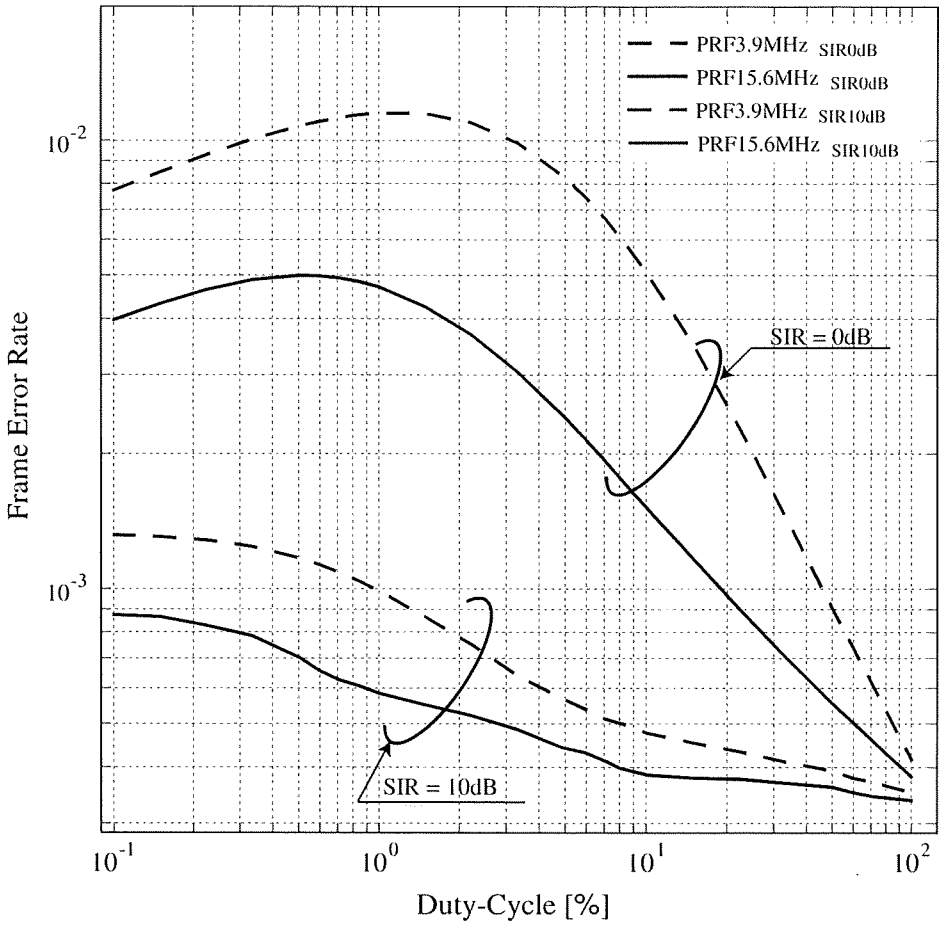

Fig. 9 The FER of the wideband OFDM system with the interference by the LDC-UWB communication devices with random polarity, when SNR = 10 dB. The definition of UWB transmission power is fixed power per unit of time

We can conclude that LDC algorithm is an efficient interference mitigation technique for low data rate UWB communication since the FER of wideband OFDM systems is improved with decreasing of the duty-cycle of LDC-UWB. However, LDC cannot suppress interference to wideband OFDM systems completely. Though, it can be mitigated moderately without additional complexity such as DAA. Thus, the duty-cycle of LDC-UWB should be chosen carefully in consideration of the quality of the service required by the wideband OFDM system in the physical layer. Moreover, the duty-cycle of LDC-UWB system should be chosen carefully in consideration of the requirements of the each LDC-UWB application.

References

1. FCC. (2002). First Report and Order: In the matter of Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems. FCC 02-48, April 2002.
2. Win, M. Z., & Scholtz, R. (2000). Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications. *IEEE Transaction on Communication, 48*(4), 679–691.
3. Freescale Semiconductor, Inc. (2005). UWB mask proposal for industry. *International Telecommunication Union Radio Communication Study Group*, document -8/429-E, October 2005.
4. Zasowski, T., & Wittneben, A. (2006). Performance of UWB systems using a temporal detect-and-avoid mechanism. In *The international conference on ultra-wideband*, September 2006.
5. Somayazulu, V. S., Foerster, J. R., & Roberts, R. D. (2006). Detect and Avoid (DAA) Mechanisms for UWB Interference Mitigation. In *The international conference on ultra-wideband*, September 2006.

6. Kogane, R., Fujii, M., Itami, M., & Itoh, K. (2006). A study on the detection scheme of the 4G signal for FSS operation in MB-OFDM. IEICE Technical Report, WBS2006-12, pp. 25–30, July 2006.
7. Yamaguchi, H. (2006). Detection-and-Avoidance (DAA) Technology for UWB—Challenges to share the frequency resource. IEICE Technical Report, WBS2005-76, pp. 11–18, March 2006.
8. Durantini, A., Giuliano, R., Mazzenga, F., & Vatalaro, F. (2006). Performance Evaluation of detect and avoid procedures for improving UWB coexistence with UMTS and WiMAX systems. In *The 2006 IEEE international conference on ultra-wideband*, pp. 501–506, September 2006.
9. Cuomo, F., Martello, C., Baicchi, A., & Capriotti, F. (2002). Radio resource sharing for ad hoc networking with UWB. *IEEE Journal on Selected Area in Communications, 20*(9), 229–239.
10. Gargin, D. J. (2004). A fast and reliable acquisition scheme for detection ultra wideband impulse radio signals in the presence of multi-path and multiple access interference. In *Ultra wideband systems 2004 joint with conference on Ultra Wideband Systems and Technologies*, pp. 106–110, May 2004.
11. Yamaguchi, H. (2004). Active interference cancellation technique for MB-OFDM Cognitive Radio. In *34th European microwave conference*.
12. Batra, A., Balakrishnan, J., Aiello, G. R., Foerster, J. R., & Dabak, A. (2004). Design of a multiband OFDM system for realistic UWB channel environments. *IEEE Transaction on Microwave Theory and Techniques, 52*(9), 2139–2147.
13. Jamieson, K., Hull, B., Miu, A., & Balakrishnan, H. (2005). Understanding the real-world performance of carrier sense. In *Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis*.
14. Polastre, J., Hill, J., & Culler, D. V. (2004). Low-power media access for wireless sensor networks. In *Proceedings of the ACM sensys conference*, pp. 95–107, November 2004.
15. Nakao, Y., Watanabe, K., Sato, T., & Kohno, R. (2007). A study on coexistence of WLAN and WPAN using PAN Coordinator with array antenna. SDR Forum 2007 Technical conference and product exposition, November 2007.
16. Callaway, E. (2001). Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs). doc.: IEEE 802.15-01/188r1, May 2001.
17. Ye, W., & Heidemann, J. (2005). Ultra-low duty cycle MAC with scheduled channel polling. USC/ISI Technical Report ISI-TR-604, July 2005.
18. Lovelace, W. M., & Townsend, J. K. (2003). Chip discrimination for near far power ratios in UWB networks. In *Military communications conference 2003 (MILCOM 2003)*, October 2003.
19. Lovelace, W. M., & Townsend, J. K. (2003). Adaptive rate control with chip discrimination in UWB. In *IEEE conference on ultra wideband systems and technologies 2003*, November 2003.
20. Ali, M., & Uzmi, Z. A. (2006). Medium access control with mobility-adaptive mechanisms for wireless sensor networks. *International Journal of Sensor Networks 2006, 1*(3/4), 134–142.
21. Tomoki, A., Pasya, I., & Kobayashi, T. (2003). Simulation of interference effects from MB-OFDM and DS-UWB to a QPSK digital transmission system. *International symposium on ultra wideband systems*, January 2003.
22. Peled, A., & Ruiz, A. (1980). Frequency domain data transmission using reduced computational complexity algorithms. *Proceedings of the IEEE international conference on acoustics*, Denver, pp. 964–967.
23. Fazel, K., & Kaiser, S. (2003). Multi-carrier and spread spectrum systems. England: Wiley, ISBN 0-470-84899-5.

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